ANNUAL PROJECT SUMMARY

AWARD NUMBER: 01HQAG0035

THE BARD CONTINUOUS GPS NETWORK: MONITORING ACTIVE DEFORMATION AND STRAIN ACCUMULATION IN NORTHERN CALIFORNIA AND THE SAN FRANCISCO BAY AREA:

Collaborative research with UC Berkeley,
and U.S. Geological Survey, Menlo Park

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PROGRAM ELEMENTS: I & II

KEY WORDS: GPS-Continuous, Surface Deformation, Fault Stress Interactions

INVESTIGATIONS UNDERTAKEN

The Bay Area Regional Deformation (BARD) network of continuously operating Global Positioning System (GPS) receivers monitors crustal deformation in the San Francisco Bay area ("Bay Area") and northern California (*Murray et al.*, 1998a). It is a cooperative effort of the BSL, the USGS, and several other academic, commercial, and governmental institutions. Started by the USGS in 1991 with 2 stations spanning the Hayward fault (*King et al.*, 1995), BARD now includes 67 permanent stations (Figure 1) and will expand to about ∼75 stations by July 2003. The principal goals of the BARD network are: 1) to determine the distribution of deformation in northern California across the wide Pacific–North America plate boundary from the Sierras to the Farallon Islands; 2) to estimate three-dimensional interseismic strain accumulation along the San Andreas fault (SAF) system in the Bay Area to assess seismic hazards; 3) to monitor hazardous faults and volcanoes for emergency response management; and 4) to provide infrastructure for geodetic data management and processing in northern California in support of related efforts within the BARD Consortium and with surveying, meteorological, and other interested communities.

During the past year, the BSL performed maintenance to existing stations, installed a new station and an experimental single-frequency receiver profile, and improved processing methods, and analysis of the data to estimate deformation signals monitored by the network.

RESULTS

Continuous GPS Measurements in Northern California

BARD currently includes 67 continuously operating stations, 34 in the Bay Area and northern California, 15 near Parkfield, along the central San Andreas fault, and 18 near the Long Valley caldera near Mammoth. The BSL maintains 21 stations (including 2 with equipment provided by

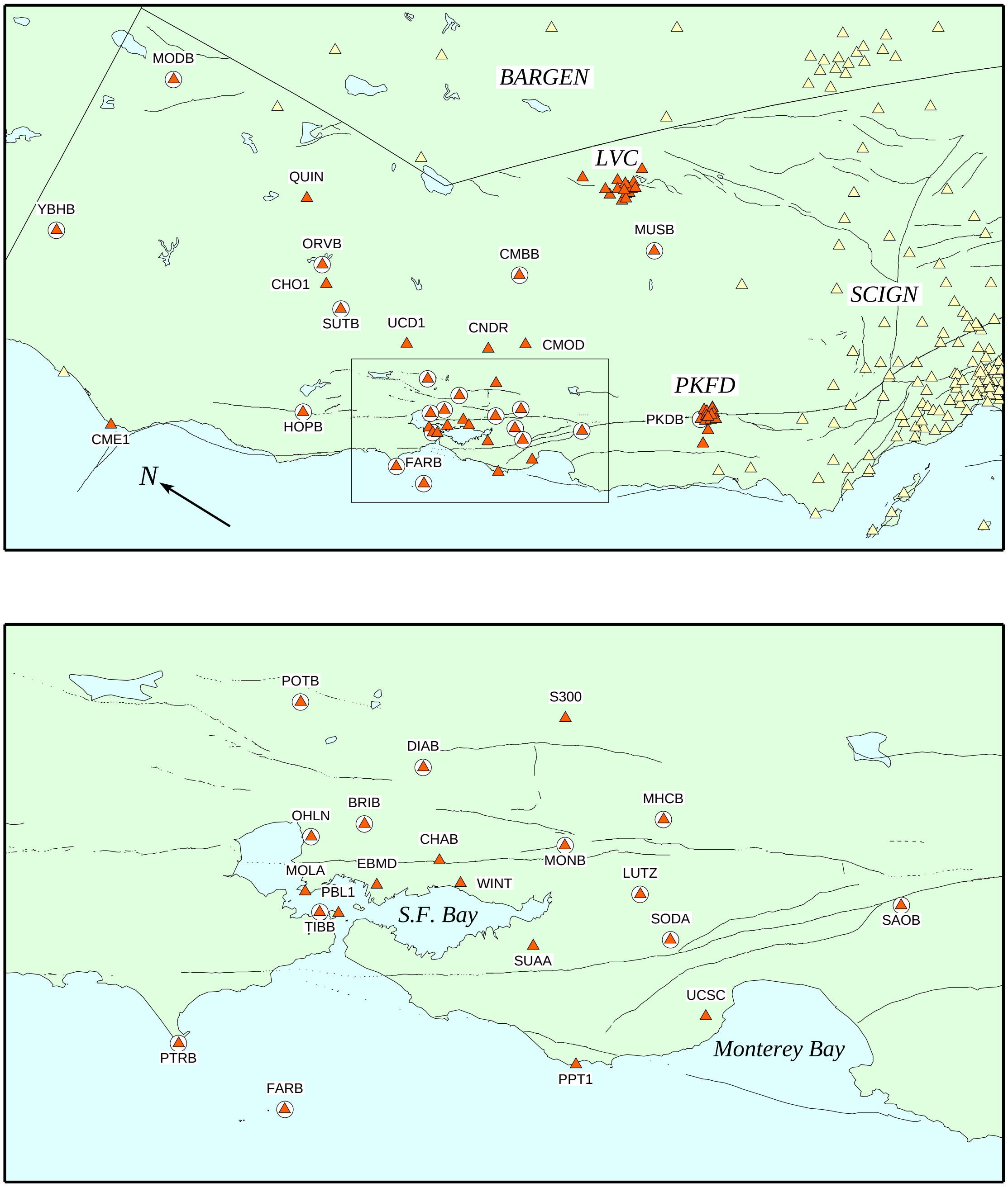

Figure 1: Operational BARD stations (red triangles) in northern California (top) and in the San Francisco Bay area (bottom). The oblique Mercator projection is about the NUVEL-1 Pacific–North America Euler pole so that expected relative plate motion is parallel to the horizontal. Circled stations use continuous telemetry. The 18 station Long Valley Caldera (LVC) network and 15 station Parkfield (PKFD) networks are also part of BARD. Other nearby networks (yellow triangles) include: Basin and Range (BARGEN), and Southern California Integrated GPS Network (SCIGN).

Lawrence Livermore National Laboratory (LLNL) and UC Santa Cruz). Other stations are maintained by the USGS (Menlo Park and Cascade Volcano Observatory), LLNL, Stanford University, UC Davis, UC Santa Cruz, and East Bay Municipal Utilities District, the City of Modesto, the National Geodetic Survey, and the Jet Propulsion Laboratory. Many of these stations are part of larger networks devoted to real-time navigation, orbit determination, and crustal deformation. The network includes several profiles between the Farallon Islands and the Sierra Nevada in order to better characterize the larger scale deformation field in northern California (Figure 1).

Many of the recent enhancements to the BARD network have been accomplished under an ongoing complementary project. The Integrated Instrumentation Program for Broadband Observations of Plate Boundary Deformation, commonly referred to as “Mini-PBO”, is a joint project of the BSL, the Department of Terrestrial Magnetism at Carnegie Institution of Washington (CIW), the IGPP at UC San Diego (UCSD), and the U.S. Geological Survey (USGS) at Menlo Park, Calif. It augments existing infrastructure in central California to form an integrated pilot system of instrumentation for the study of plate boundary deformation, with special emphasis on its relation to earthquakes. This project is partially funded through the EAR NSF/IF program with matching funds from the participating institutions and the Southern California Integrated Geodetic Network (SCIGN). It has several components, including support for an InSAR facility in San Diego to collect and archive radar data, and develop an online SAR database for WInSAR users. The other two components include GPS instrumentation that are now included in the BARD network.

Mini-PBO Station Installations

The Mini-PBO program supports installation of stations along the Hayward and San Andreas faults in the San Francisco Bay area to complement existing instrumentation (Figure 2). From July 2001 to August 2002, five boreholes were drilled and equipped with tensor strainmeters and 3-component L22 (velocity) seismometers. The strainmeters were recently developed by by CIW and use 3 sensing volumes placed in an annulus with 120 degree angular separation, which allows the 3-component horizontal strain tensor to be determined. The borehole station in Ohlone Park in Hercules (OHLN) has also been equipped with a GPS receiver, Quanterra recording system, and downhole pore pressure sensor, and will eventully also include a tilt sensor. The other stations are in various stages of completion, primarily waiting for power and telemetry to be established.

The BSL is developing an experimental GPS mount for the top of the borehole casings to create a stable, compact monument (Figure 3). The antennas, using standard SCIGN adapters and domes for protection, are attached to the top of the 6-inch metal casing, which will be mechanically isolated from the upper few meters of the ground. The casing below this level will be cemented fully to the surrounding rock. At OHLN, the antenna is attached to a metal pipe symmetrically centered with respect to the casing that is welded to a cross beam and bolted inside the top of the casing, which allows access through the top of the casing to the 2” pipe for heat flow measurements (Figure 4). A similar mount was constructed at OXMT, near Half Moon Bay, but it was found to have too much play in the area where the bolts are attached to ensure long-term stability of the monument. We are redesigning the mount to minimize such non-tectonic motions. The current design uses a flange that is permanently attached to the top of the casing, which allows access to the borehole for instrument maintenance, and a top plate with the vertical pipe and antenna adapter that is bolted to the flange. Several dowels between the flange and top plate ensure that the top plate can be removed and reattached with better than 0.1 mm repeatability.

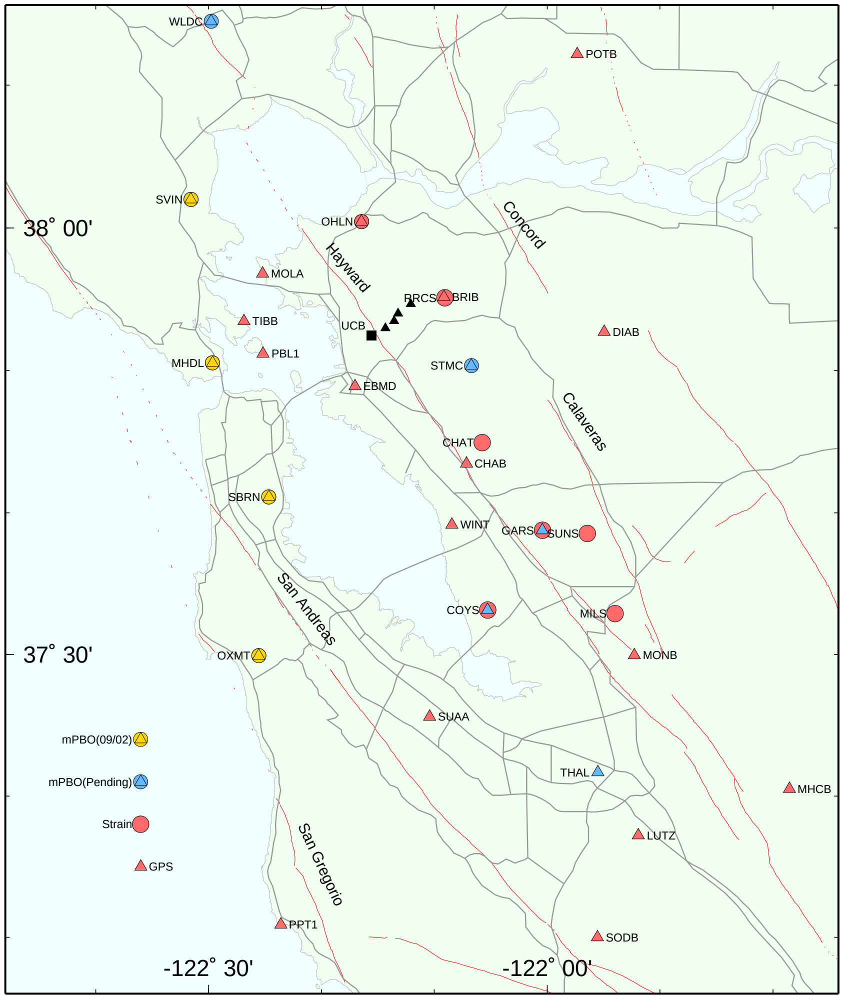

Figure 2: Location of existing (red), in preparation (yellow), and pending (blue) Mini-PBO sites in the San Francisco Bay area. Shown also (red) are currently operating strainmeter (circles) and BARD (triangles) stations. Blue triangles are other pending BARD stations. Black triangles are L1-system profile sites near the Hayward fault and the UC Berkeley campus.

Preliminary analysis of 100 days of the GPS observations at OHLN shows that the short-term daily repeatabilities in the horizontal components are about 0.5-1 mm. These values are similar to those obtained with more typical monuments, such as concrete piers or braced monuments, but it is too early to assess the long-term stability of the borehole casing monument, which might also be affected by annual thermal expansion effects on the casing.

The 30-second GPS, and 100-Hz strainmeter and seismometer data is acquired on Quanterra data loggers and continuously telemetered by frame relay to the BSL. Low frequency (600 second) data (including strainmeters, for redundancy) is telemetered using the GOES system to the USGS. All data is available to the community through the Northern California Earthquake Data Center (NCEDC) in SEED format, using procedures developed by the BSL and USGS to archive similar data from 139 sites of the USGS ultra-low-frequency (UL) geophysical network, including data

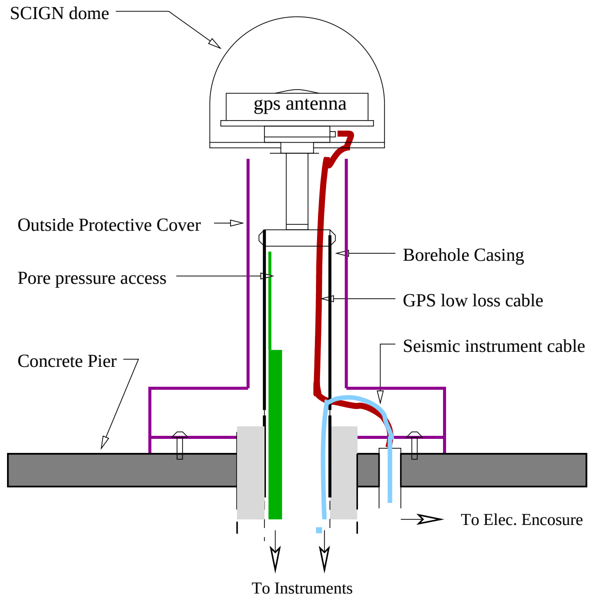

Figure 3: Design of the Mini-PBO GPS antenna mount on top of casing.

Figure 4: GPS antenna mounted on top of casing at OHLN. The final installation includes a SCIGN antenna dome and a steel protective shroud that envelopes the casing.

from strainmeters, tiltmeters, creep meters, magnetometers, and water well levels.

The second component of this project is to link the BARD network in central and northern California to the SCIGN network in southern California. The distribution of these sites allows measurement of both near-field deformation from fault slip on the San Andreas and regional strain accumulation from far-field stations. During Summer 2001, nine new continuous GPS sites were installed in the Parkfield area spanning about 25 km on either side of the San Andreas fault. One of the receivers was contributed by the USGS and the other eight were contributed by SCIGN, while the braced monuments for all the sites were constructed using Mini-PBO funding. The new array augments the considerable geophysical instrumentation already deployed in the area and contributes to the deep borehole drilling on the San Andreas fault (SAFOD) component of Earthscope. Although data are currently downloaded daily by SCIGN and archived by SOPAC, the NCEDC will assume the responsibility for retrieving the data from these sites over their existing frame relay circuit at Parkfield. We are currently readying a Linux computer to control the data download at Carr Hill. A subset of the GPS sites will eventually be upgraded to real-time streaming and analyzed in instantaneous positioning mode.

L1-system Profile

The BSL staff is evaluating the performance of the UNAVCO-designed L1 system in an urban setting. This single-frequency receiver is relatively inexpensive but is less accurate than dual-frequency receiver systems that can completely eliminate first-order ionospheric effects. Hence we expect the L1 system to be most useful for short baseline measurements where ionospheric

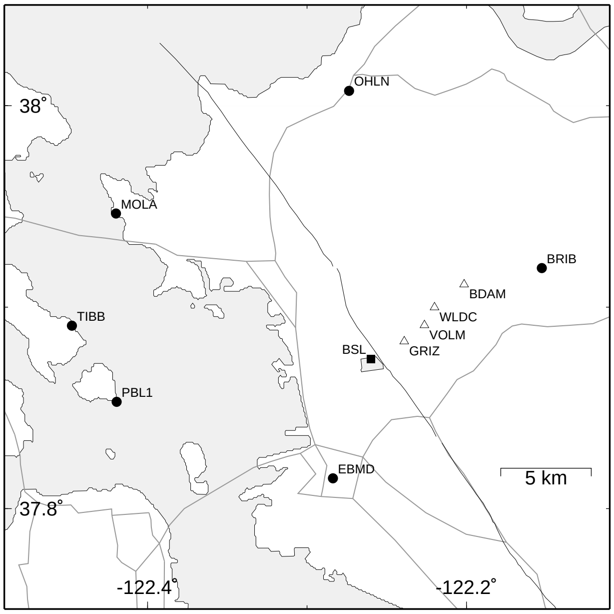

Figure 5: Location of L1-system (open triangles) and BARD (closed circles) stations. BSL, just southwest of the Hayward fault, is the location of the Berkeley Seismological Laboratory, where data from the 4 L1-system receivers northeast of the Hayward are telemetered.

Figure 6: L1 system installation at GRIZ. This autonomous system uses solar panels (mounted in back) and Freewave radios (with Yagi antenna mounded on pole below GPS antenna). GPS receiver, radio, solar power regulators, and backup batteries are in the electronics box mounted in front.

effects tend to cancel due to similar propagation paths. The systems are self-contained, using solar power and integrated radio modems. During 1999, the BSL borrowed 2 receivers and a master radio from UNAVCO to perform the evaluation, but persistent hardware and software problems limited progress on this project. UNAVCO subsequently resolved many of the problems and in summer 2000, we received new, improved equipment and software for 4 systems and a master radio.

During 2000 and 2001, we completed permitting at 4 sites on a 10-km profile extending normal to the Hayward fault between the UC Berkeley campus and the permanent BRIB site (Fig. 5). The station BDAM is located just east of the Briones Dam and a few km west of the Briones (BRIB) continuous BARD station. Wildcat (WLDC) is located near the San Pablo Reservoir, and VOLM is located on the ridge of the East Bay Hills close to Volmer Peak. The fourth site, Grizzly Flat (GRIZ), is located just west of Grizzly Peak. Finding suitable stations with line-of-sight telemetry across the East Bay Hills proved challenging. Data from WLDC must pass through all the other stations, with its relay path being (in order) BDAM, VOLM, GRIZ, a repeater on the UC Berkeley Space Sciences Building, and then finally the master radio on the roof of McCone Hall where the BSL is located on campus. This profile, complemented by BRIB to the east and EBMD to the west of the fault, will be most sensitive to variations in locking at 2-8 km depth. We expect that these systems will provide useful constraints on relative displacements near the Hayward fault in 3–5 years, and should help to resolve variations in creeping and locked portions of the fault (e.g., *Bürgmann et al*, 2000).

In April 2002, we installed the L1 Profile with assistance from two engineers from UNAVCO. We used a large gas powered hand drill to bore a 2” diameter, 18” deep hole into bedrock at the BDAM and VOLM sites, and cemented in a galvanized pipe using expansive grout. GRIZ and WLDC are located in areas where we could not easily access bedrock. GRIZ is located on top of a small plateau covered in volcanic deposits that have weathered to clay. Bedrock was observed nearby uphill of the WLDC site, but could not be used due to telemetry constraints. At both of these sites a subsurface concrete pier was constructed, laced with chicken wire to reduce cement fracturing during drying, and anchored by steel rebar pounded into the ground at several angles.

The electronics, including gps/radio unit, battery and solar power manager, are securely stored within a medium-sized Hoffman box, or locking metal enclosure, attached to pipe. Whenever possible access to the inside of box is necessary to remove bolts attaching the box itself. GPS antenna is mounted on a fiberglass rod attached to top of pipe. All loose cables are zip-tied in place and all stainless steel bolts are epoxied to discourage theft. A typical site, with a Yagi antenna for communications, is shown in Figure 6.

Since April, we have been assessing the data quality and processing the data to estimate daily site positions. Problems with telemetry outages at WLDC during the early morning, pre-dawn hours, were found to be due to a faulty battery, and were corrected when we installed new batteries at all the sites. GRIZ currently is experiencing intermittent data outages which were not solved by the new battery or by replacing the receiver/radio unit. We are currently investigating possible problems with the solar power regulator. We are also in the process of obtaining 2 additional systems from UNAVCO that will be installed on the roofs of the Space Sciences and McCone Hall buildings, which will make the profile cross the Hayward fault and allow direct measurement of surface creep in this region.

We are developing techniques to process the data using the GAMIT/GLOBK analysis package. We corrected software provided by UNAVCO to synchronize the phase, pseudorange, and clock offset observables, which allows the data to be cleaned in an automatic fashion. Preliminary results suggest that repeatabilities of 1–2 mm in daily horizontal positions on the shortest (several km) baselines can be achieved (Figure 7), but these degrade to 3–4 mm on the longer (10 km) baselines. We are investigating ways to simultaneously process the dual-frequency data from nearby BARD stations (e.g., BRIB, OHLN), with the single-frequency L1 data to improve these results. Currently data from second frequency on the BARD stations is not used, which degrades the definition of the local reference frame and repeatability of the baselines.

Existing Station Maintenance

In March 2002, “copper-miners” took advantage of of the poor security at the decommissioned Point Molates naval facility to fell the power poles and remove high tension copper power lines that were used by the MOLA station. The property has been put aside for environmental cleanup before the ownership is transferred from the Navy to the City of Richmond. Due to the status of the property, the high costs to reestablish power, and the unsecured nature of the area, the station was removed from continuous GPS service. The monument and enclosure were left intact and the site is being be periodically reoccupied, approximately 2–3 days per month, in a semi-permanent mode.

In May 2002, forced entry in the building housing the GPS equipment at SAOB resulted in theft of GPS receiver and damage to building and telemetry system. We reinforced the plywood building walls with a layer of wire mesh followed by a surface layer of plywood secured with screws and liquid adhesive. Inside the building, the GPS receiver and short-haul modems where replaced and stored within a double locked large metal "Hoffman" box.

Also in May 2002, the receiver and Freewave radio at Sutter Buttes (SUTB) were replaced due to a data outage following an electrical storm and possible lightning strike. The site is located on top of the South Butte, 2000 feet above the Central Valley.

Data Archival and Distribution

Today, raw and Rinex data files from the BSL stations and the other stations run by BARD collaborators are archived at the BSL/USGS Northern California Earthquake Data Center data archive maintained at the BSL (*Romanowicz et al.*, 1994). The data are checked to verify their integrity, quality, completeness, and conformance to the RINEX standard, and are then made accessible, usually within 2 hours of collection, to all BARD participants and other members of the GPS community through Internet, both by anonymous ftp and by the World Wide Web (`http://quake.geo.berkeley.edu/bard/`).

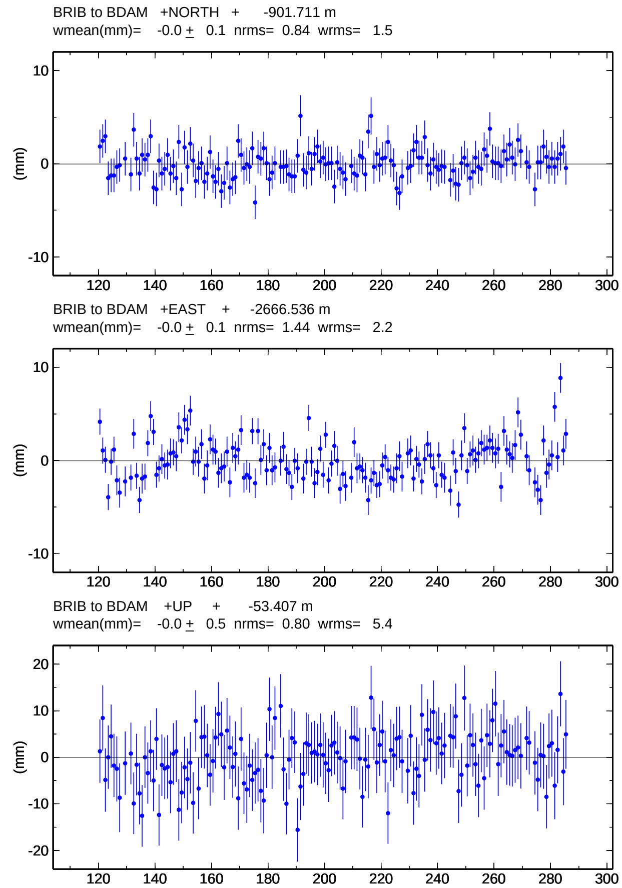

Figure 7: Daily estimates of the north, east, and up components of the BRIB to BDAM 1-km baseline. Daily repeatabilities are about 1-2 mm in the horizontals and 5 mm in the vertical.

Data and ancillary information about BARD stations are also made compatible with standards set by the International GPS Service (IGS), which administers the global tracking network used to estimate precise orbits and has been instrumental in coordinating the efforts of other regional tracking networks. The NCEDC also retrieves data from other GPS archives, such as at SIO, JPL, and NGS, in order to provide a complete archive of all high-precision continuous GPS measurements collected in northern California.

Many of the BARD sites are classified as CORS stations by the NGS, which are used as reference stations by the surveying community. All continuous stations operating in July 1998 and May 2000 were included in a statewide adjustments of WGS84 coordinates for this purpose. Members of the

BARD project regularly discuss these and other common issues with the surveying community at meetings of the Northern California GPS Users Group and the California Spatial Reference Center.

Since 1997, the NCEDC has collaborated with UNAVCO and other members of the GPS community on the development of the GPS Seamless Archive Centers (GSAC) project. When completed, this project will allow a user to access the most current version of GPS data and metadata from distributed archive locations. The NCEDC is participating at several levels in the GSAC project: as a primary provider of data collected from core BARD stations and USGS MP surveys, as a wholesale collection point for other data collected in northern California, and as a retail provider for the global distribution of all data archived within the GSAC system. We have helped to define database schema and file formats for the GSAC project, and for several years have produced complete and incremental monumentation and data holdings files describing the data sets that are produced by the BARD project or archived at the NCEDC so that other members of the GSAC community can provide up-to-date information about our holdings. Currently, the NCEDC is the primary provider for over 74,000 data files from over 1400 continuous and survey-mode monuments. The data holdings records for these data have been incorporated into a preliminary version of the retailer system currently undergoing testing, which should become publicly available in late 2002.

Data Analysis and Results

The data from the BARD sites generally are of high quality and measure relative horizontal positions at the 2–4 mm level. The 24-hour RINEX data files are processed daily with an automated system using high-precision IGS orbits. Final IGS orbits, available within 7–10 days of the end of a GPS week, are used for final solutions. Preliminary solutions for network integrity checks and rapid fault monitoring are also estimated from Predicted IGS orbits (available on the same day) and from Rapid IGS orbits (available within 1 day). Data from 5 primary IGS fiducial sites located in North America and Hawaii are included in the solutions to help define a global reference frame. Average station coordinates are estimated from 24 hours of observations using the GAMIT software developed at MIT and SIO, and the solutions are output with weakly constrained station coordinates and satellite state vectors.

Processing of data from the BARD and other nearby networks is split into 7 geographical subregions: the Bay Area, northern California, Long Valley caldera, Parkfield, southern and northern Pacific Northwest, and the Basin and Range Province. Each subnet includes the 5 IGS stations and 3 stations in common with another subnet to help tie the subnets together. The weakly constrained solutions are combined using the GLOBK software developed at MIT, which uses Kalman filter techniques and allows tight constraints to be imposed a posteriori. This helps to ensure a self-consistent reference frame for the final combined solution. The subnet solutions for each day are combined assuming a common orbit to estimate weakly constrained coordinate-only solutions. These daily coordinate-only solutions are then combined with tight coordinate constraints to estimate day-to-day coordinate repeatabilities, temporal variations, and site velocities.

The estimated relative baseline determinations typically have 2–4 mm WRMS scatter about a linear fit to changes in north and east components and the 10–20 mm WRMS scatter in the vertical component. Average velocities for the longest running BARD stations during 1993–2000 are shown in Figure 8, with 95% confidence regions. We have allowed $1mm/\sqrt{yr}$ random-walk variations in the site positions in order to more accurate characterization of the long-term stability of the site monuments and day-to-day correlations in position. The velocities are relative to stable

North America, as defined by the IGS fiducial stations, which we assume have relative motions given by *Kogan et al.,* (2000).

Most of the Sierra Nevada sites (CMBB, QUIN, and ORVB), as well as SUTB in the Central Valley, show little relative motion, indicating that the northern Sierra Nevada–Central Valley is tectonically stable. The motion of these sites relative to North America differs from the inferred motion of the western Basin and Range Province, suggesting 3 mm/yr right-lateral shear across the Walker Lane-Mt. Shasta seismicity trend. Deformation in the Pacific Northwest is generally consistent with interseismic strain accumulation along the Cascadia megathrust, the interface between the Juan de Fuca and North America plates, particularly in Washington where the velocity vectors are nearly parallel to the oblique convergence direction. Greater arc-parallel motion in Oregon and northern California may be due to the influence of the SAF system to the south and clockwise rotation of the southern Oregon forearc (*Savage et al.,* 2000).

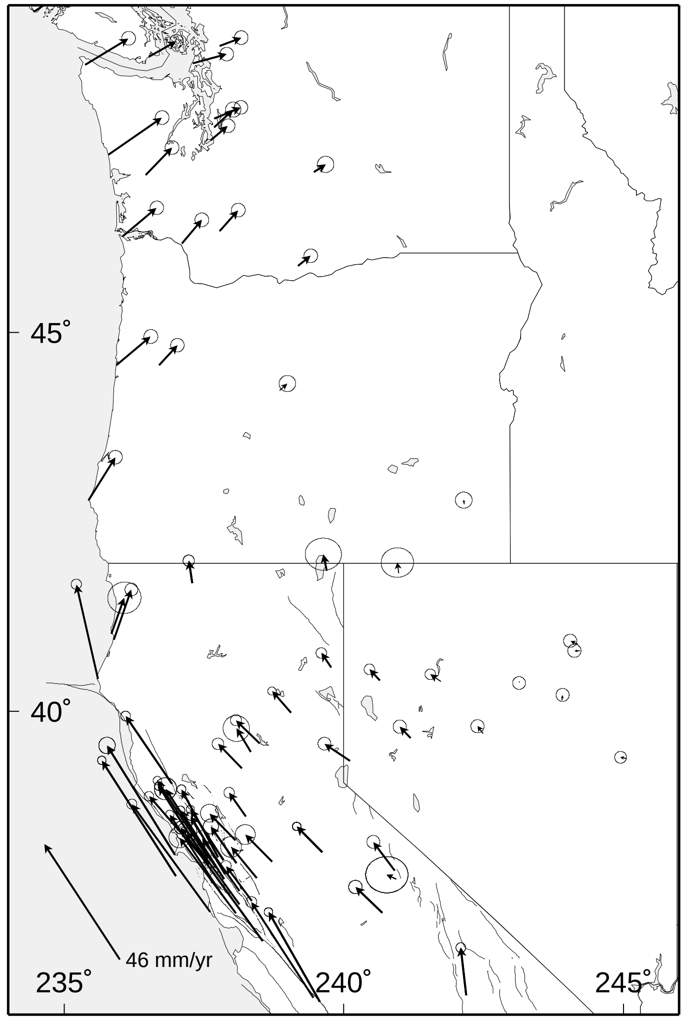

Figure 8: Velocities relative to stable North America for the BARD stations and other stations operated in nearby networks. Data from November 1993 to July 2000 was processed by the BSL using GAMIT software. Ellipses show 95% confidence regions, assuming white noise and $1mm/\sqrt{yr}$ random-walk noise, with the predicted Pacific–North America relative plate motion in central California shown for scale.

Deformation along the coast in central California is dominated by the active SAF system, which accommodates about 35 mm/yr of right-lateral shear. The Farallon Island site (FARB) off the coast of San Francisco is moving at nearly the rate predicted by the NUVEL-1A Pacific–North America Euler pole. Two-dimensional modeling of the observed fault-parallel strain accumulation predicts deep slip rates for the San Andreas, Hayward, and Calaveras/Concord faults are 19.3±1.8, 11.3±1.9, and 7.4±1.6 mm/yr, respectively, in good agreement with estimated geologic rates (17±4, 9±2, and 5±3 mm/yr, respectively). Most of the 46 mm/yr of relative motion is accommodated within a 100-wide zone centered on the SAF system and a broader zone in the Basin and Range Province in Nevada. The northern California and Nevada deformation field and kinematic modeling is discussed in more detail in *Murray and Segall* (2001).

Real-Time Processing

We are also developing real-time analysis techniques that will enable rapid determinations ($\sim$minutes) of deformation following major earthquakes to complement seismological information and aid determinations of earthquake location, magnitude, geometry, and strong motion (*Murray et al.,* 1998c). In northern California, rapid earthquake notification is a collaborative effort of the USGS Menlo Park and the UC Berkeley Seismological Laboratory (BSL). Notification is performed in stages as data and results become available. The USGS use data from their short-period vertical seismic network to provide preliminary locations within seconds, and final locations and preliminary coda magnitudes within 2-4 minutes. This information is used by BSL to drive the Rapid Earthquake Data Integration (REDI) processing system (*Gee et al.,* 1996; 2002). If the coda magnitude is 3.0 or greater, waveforms from the BSL broadband seismic network are analyzed to estimate local magnitude, and peak ground motions and moment tensors are estimated at higher magnitudes.

Because the point source approximation made in the moment tensor codes may break down at regional distances from $M > 7.5$ events, we have extended the seismic methodologies to estimate finite fault parameters. However, seismic data alone have difficulty determining the geometry of finite faults. Geodetic networks provide a complementary data source that can be used to independently estimate rupture parameters of $M > 6$ events, particularly for shallow events located near stations in the network. Geodetic measurements of coseismic displacements provide important constraints on earthquake faulting, including the location and extent of the rupture plane, unambiguous resolution of the nodal plane, and the distribution of slip on the fault unbiased by rupture velocity assumptions (e.g., *Murray et al.,* 1996).

We currently process data available within 1 hour of measurement from the 20 continuous telemetry BSL stations, and several other stations that make their data available on an hourly basis. The data are binned into 1 hour files and processed simultaneously. Prior to the earthquake, the station locations can be constrained at the cm-level to well-known locations, which improves resolution of carrier phase integer ambiguities. The scatter of these hourly solutions is similar to the 24-hour solutions: 2-4 mm in the horizontal and 10 mm in the vertical. After an earthquake the station locations cannot be assumed as precisely, so the uncertainties become much larger. Using 30 minutes of data, our simulations suggest that displacements 10 cm-level should be reliably detected, and that the current network should be able to resolve the finite dimensions and slip magnitude of a $M = 7$ earthquake on the Hayward fault. We are currently investigating other analysis techniques that should improve both the rapidity and precision of the postseismic position estimates using a Kalman filter techniques that can combine the most recent data with previous data in near real-time. The August 1998 $M = 5.1$ San Juan Bautista earthquake (*Uhrhammer et al.*, 1999) is the only event to have produced a detectable earthquake displacement signal at a BARD GPS receiver.

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NON-TECHNICAL ABSTRACT

We maintain the Bay Area Regional Deformation (BARD) network of permanent Global Positioning System (GPS) stations to better understand crustal deformation in northern California and the timing and hazards posed by future earthquakes caused by strain accumulation along the San Andreas fault system in the San Francisco Bay area. During the past year, we performed enhancements to the existing network and operation procedures, installed several new stations, included new broadband deformation stations equipped with GPS and borehole strainmeters and seismometers.